# The Stack & Procedures

CSE 351 Autumn 2022


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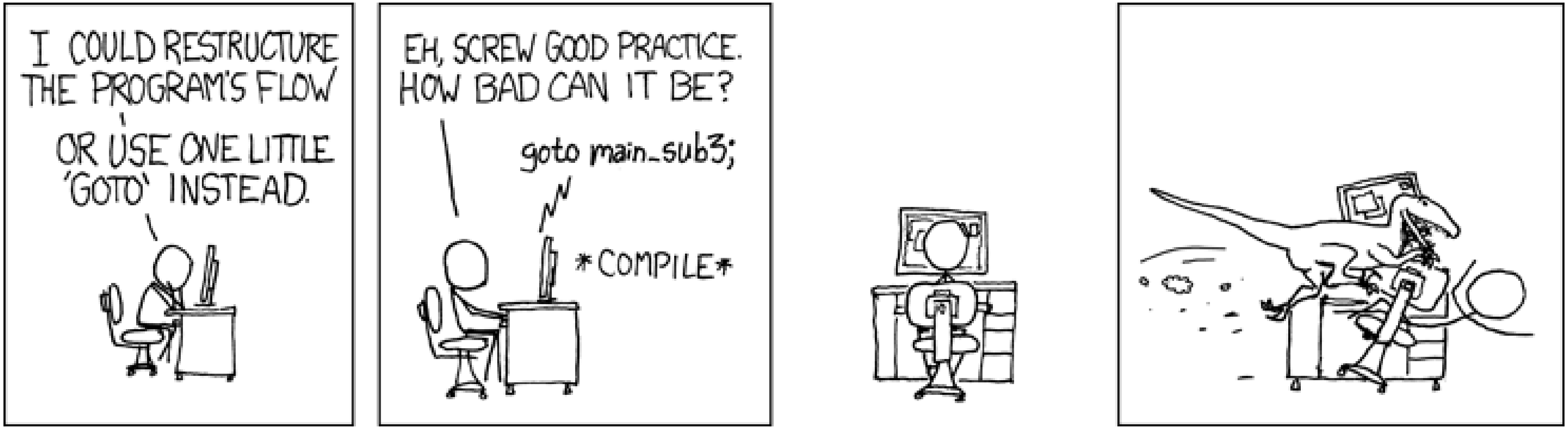



http://xkcd.com/571/

# Relevant Course Information

- Lab 2 due next Friday (10/28)
  - Can start in earnest after today's lecture!
  - See GDB Tutorial and Phase 1 walkthrough in Section 4 Lesson
- Midterm (take home, 11/3–11/5)
  - Make notes and use the midterm reference sheet
  - Form study groups and look at past exams!

# x86 Control Flow

- Condition codes
- Conditional and unconditional branches
- Loops
- **Switches**

```
long switch_ex
   (long x, long y, long z)
{
    long w = 1;
    switch (x) {
        case 1:
            w = y*z; break;
        case 2:
            w = y/z;
        /* Fall Through */
        case 3:
            w += z;  break;
        case 5:
        case 6:
            w -= z;  break;
        case 7:
            w = y%z; break;
        default:
            w = 2;
    }
    return w;
}
```

# Switch Statement Example

- Multiple case labels
  - Here: 5 & 6
- Fall through cases
  - Here: 2
- Missing cases
  - Here: 4
- Implemented with:
  - *Jump table*
  - *Indirect jump instruction*

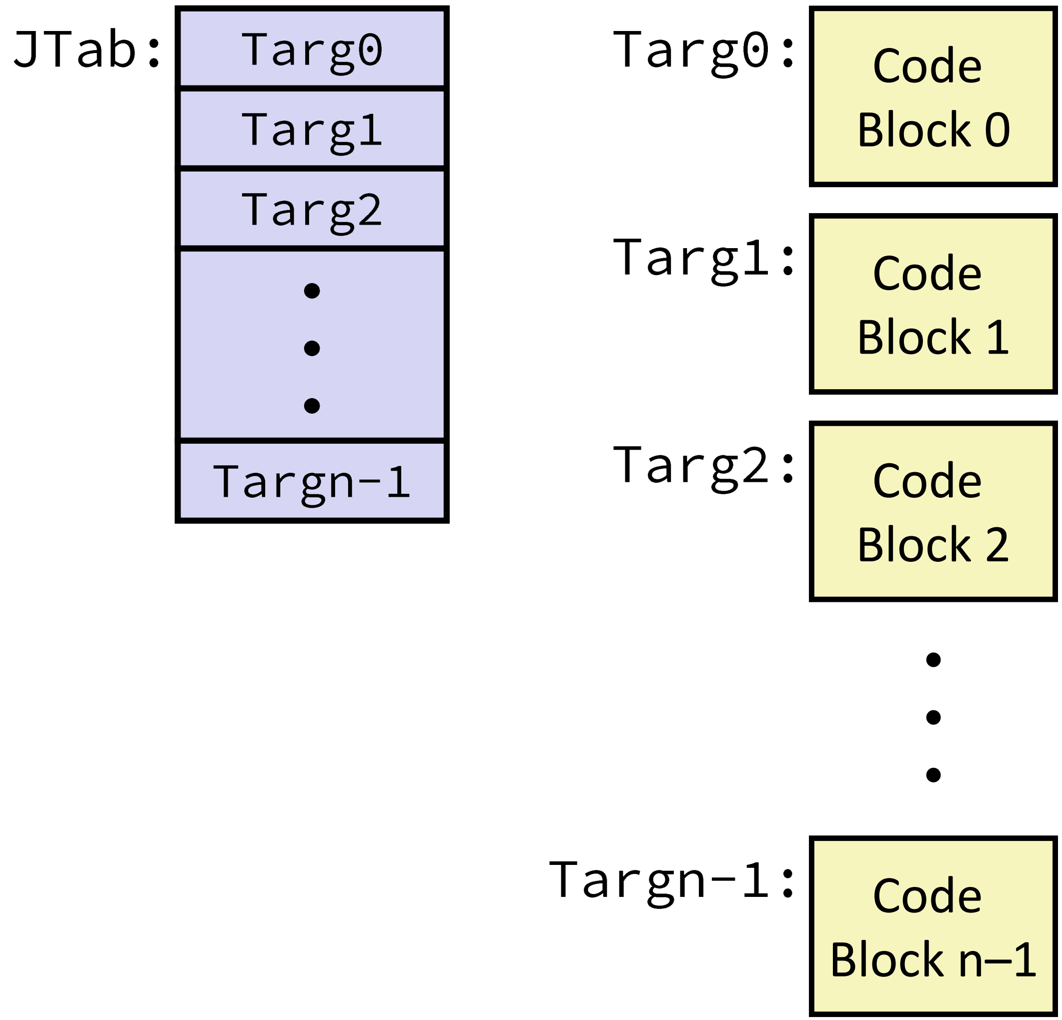
# Jump Table Structure

### Switch Form

```
switch (x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```

### Jump Table

### Jump Targets




### Approximate Translation

```
target = JTab[x];
goto target;
```

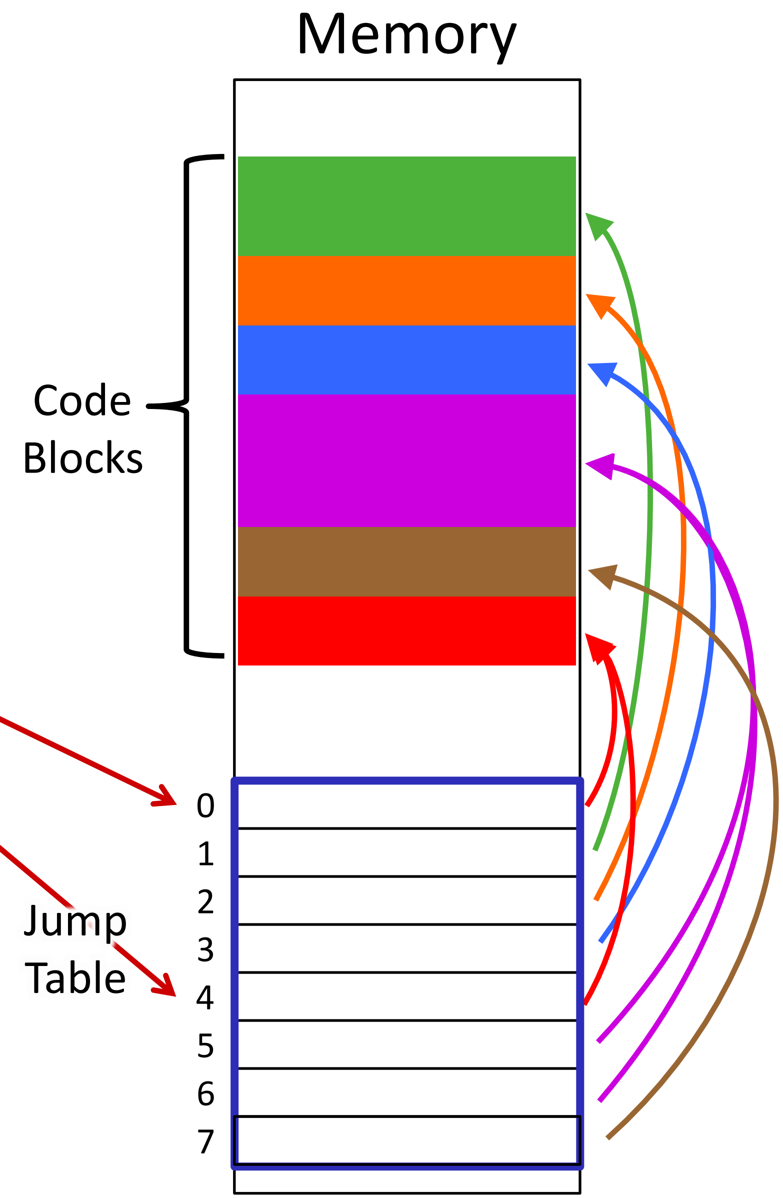
# Jump Table Structure

C code:

```
switch (x) {
  case 1: <code> break;
  case 2: <code>
  case 3: <code> break;
  case 5:
  case 6: <code> break;
  case 7: <code> break;
  default: <code>
}
```

Use the jump table when x ≤ 7:

```
if (x <= 7)
  target = JTab[x];
  goto target;
else
  goto default;
```



# Switch Statement Example

| Register | Use(s) |
|---|---|
| %rdi | 1st argument (x) |
| %rsi | 2nd argument (y) |
| %rdx | 3rd argument (z) |
| %rax | return value |

```
long switch_ex(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
    return w;
}
```

Note compiler chose to not initialize w

```
switch_ex:
    movq    %rdx, %rcx
    cmpq    $7, %rdi          # x:7
    ja      .L9               # default
    jmp     *.L4(,%rdi,8)     # jump table
```

Take a look!
https://godbolt.org/z/r8qY7Ec1T

jump above – unsigned > catches negative default cases

# Switch Statement Example

```
long switch_ex(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
    return w;
}
```

```
switch_ex:
    movq    %rdx, %rcx
    cmpq    $7, %rdi        # x:7
    ja      .L9             # default
    jmp     *.L4(,%rdi,8)   # jump table
```

***Indirect jump***

**Jump table**

```
.section    .rodata
  .align 8
.L4:
  .quad     .L9     # x = 0
  .quad     .L8     # x = 1
  .quad     .L7     # x = 2
  .quad     .L10    # x = 3
  .quad     .L9     # x = 4
  .quad     .L5     # x = 5
  .quad     .L5     # x = 6
  .quad     .L3     # x = 7
```

# Assembly Setup Explanation

- Table Structure
  - Each target requires 8 bytes (address)
  - Base address at `.L4`

**Jump table**

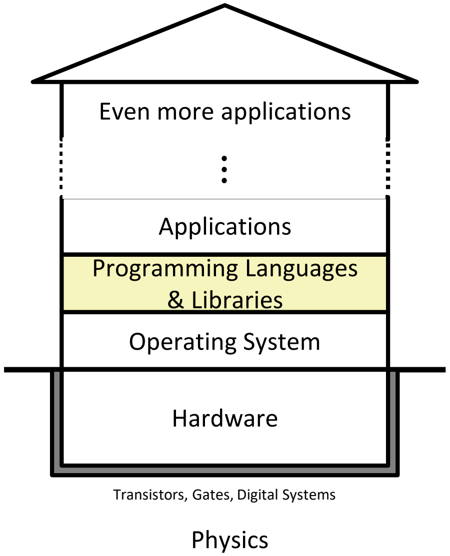
```
.section    .rodata
  .align 8
.L4:
  .quad    .L9    # x = 0
  .quad    .L8    # x = 1
  .quad    .L7    # x = 2
  .quad    .L10   # x = 3
  .quad    .L9    # x = 4
  .quad    .L5    # x = 5
  .quad    .L5    # x = 6
  .quad    .L3    # x = 7
```

- **Direct jump:** `jmp .L9`
  - Jump target is denoted by label `.L9`

- **Indirect jump:** `jmp *.L4(,%rdi,8)`
  - Start of jump table: `.L4`
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective address `.L4 + x*8`
    - Only for $0 \le x \le 7$

# The Hardware/Software Interface

- Topic Group 2: **Programs**
  - x86-64 Assembly, **Procedures**, **Stacks**, Executables




- How are programs created and executed on a CPU?
  - How does your source code become something that your computer understands?
  - How does the CPU organize and manipulate local data?

# Reading Review

- Terminology:
  - Stack, Heap, Static Data, Literals, Code
  - Stack pointer (`%rsp`), `push`, `pop`
  - Caller, callee, return address, `call`, `ret`
    - Return value: `%rax`
    - Arguments: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
  - Stack frames and stack discipline

- Questions from the Reading?

# Review Questions

- How does the stack change after executing the following instructions?

```
pushq %rbp
subq  $0x18, %rsp
```

- For the following function, which registers do we know *must* be used?

```
void* memset(void* ptr, int value, size_t num);
```

# Mechanisms required for *procedures*

1) Passing control
   - To beginning of procedure code
   - Back to return point
2) Passing data
   - Procedure arguments
   - Return value
3) Memory management
   - Allocate during procedure execution
   - Deallocate upon return

- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure

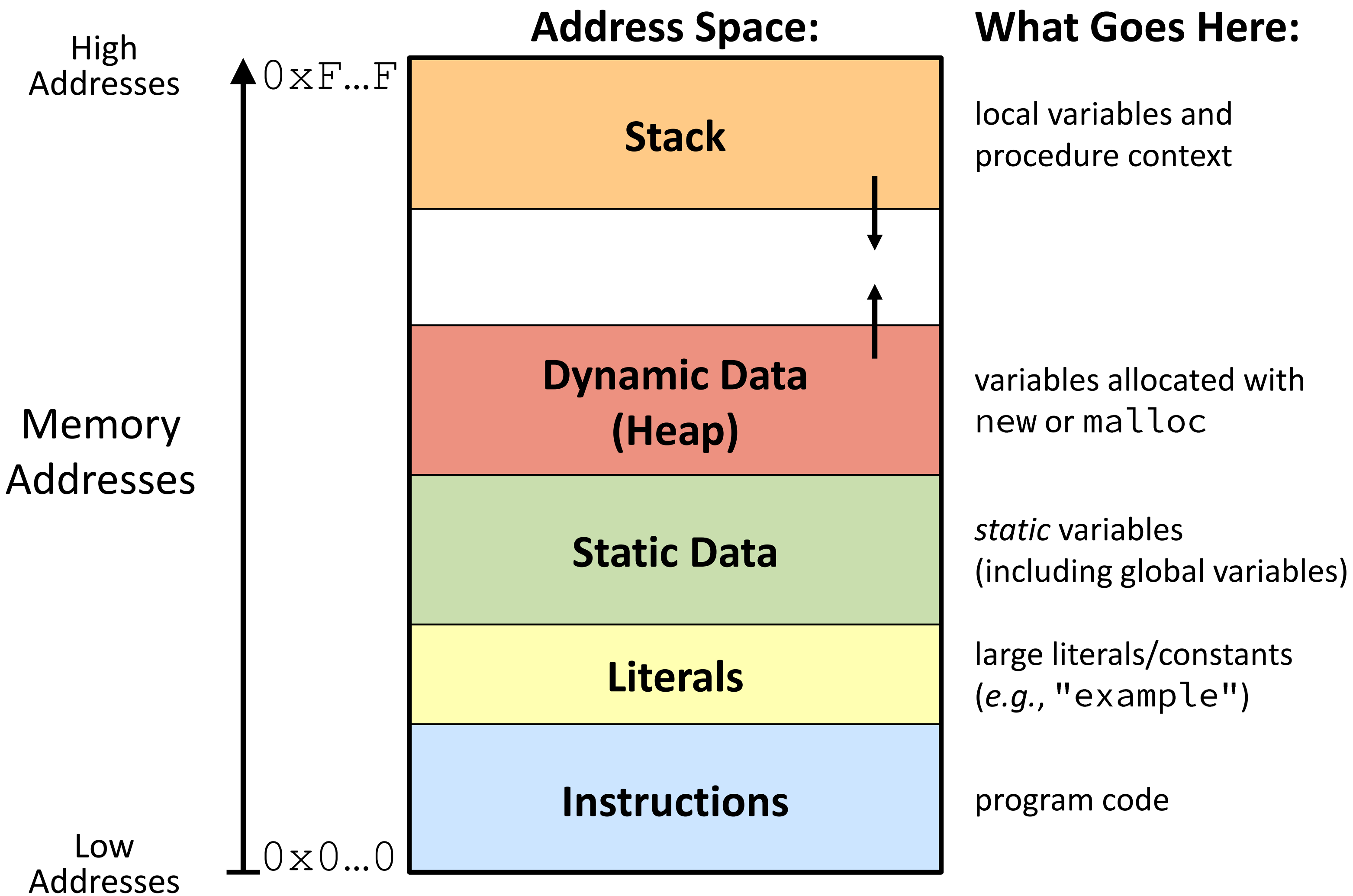
```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

# Procedures

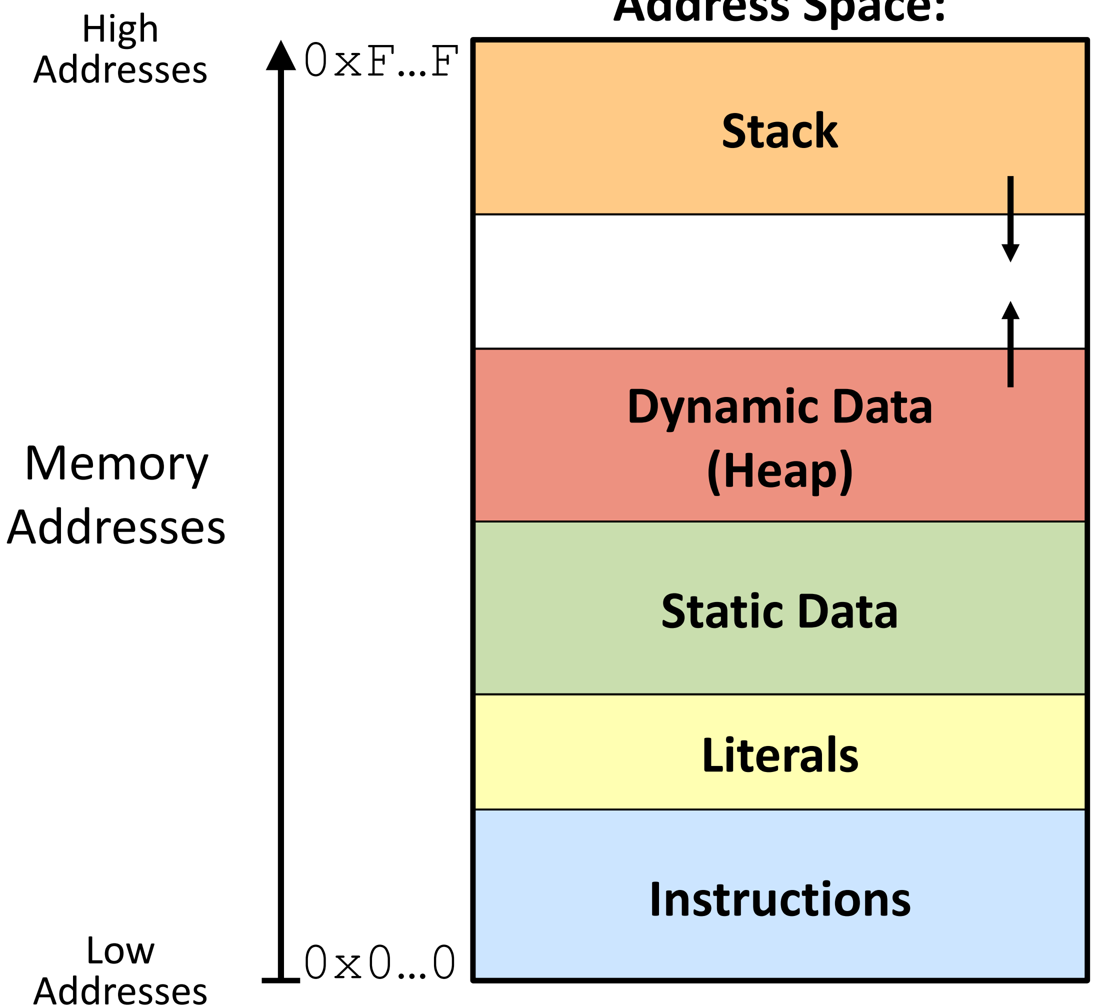
- **Stack Structure**
- Calling Conventions
  - Passing control
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

# Simplified Memory Layout (Review)



# Memory Management

**Address Space:**




**Who's Responsible:**

Managed "automatically" (by compiler/assembly)

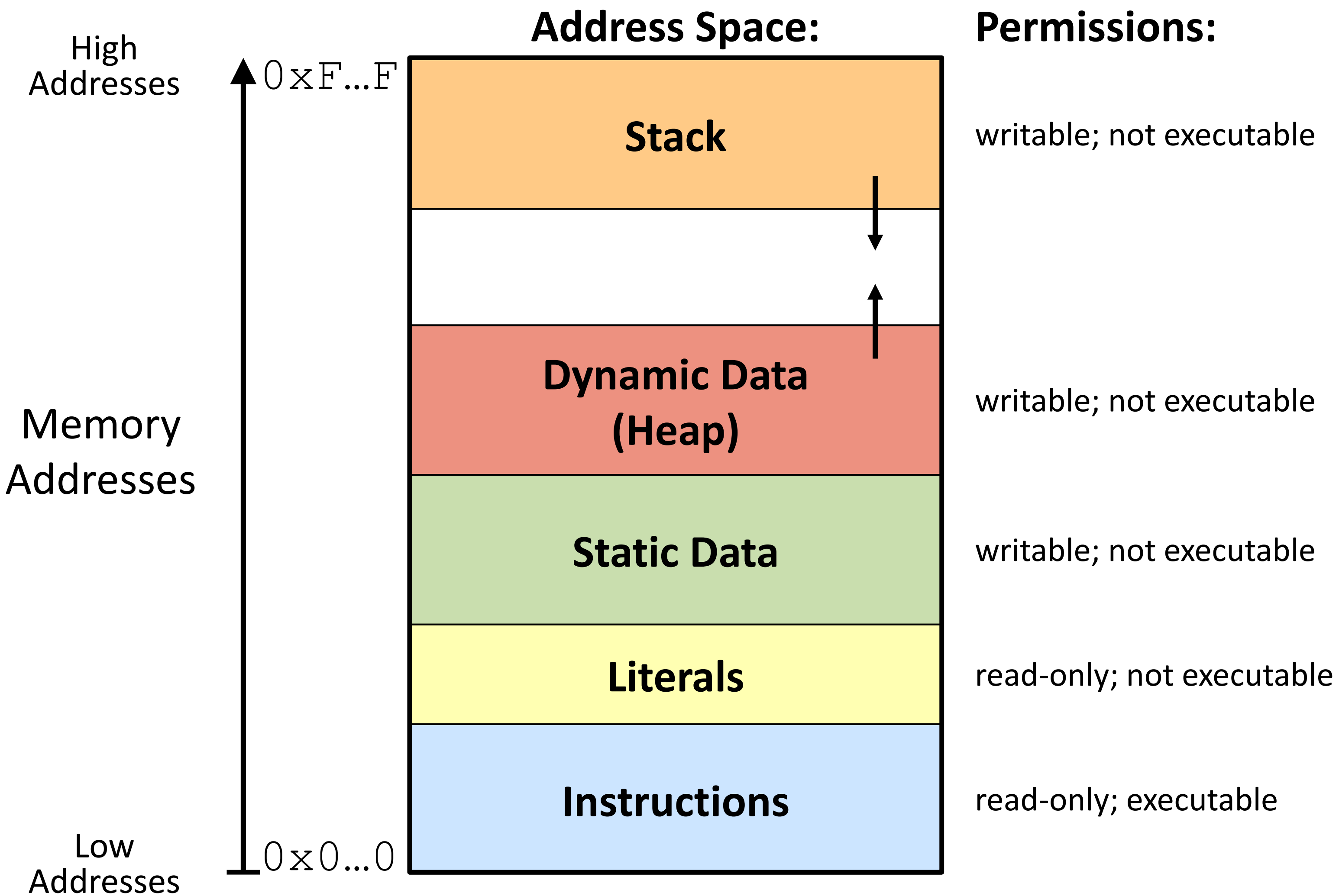
Managed "dynamically" (by programmer)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

# Memory Permissions



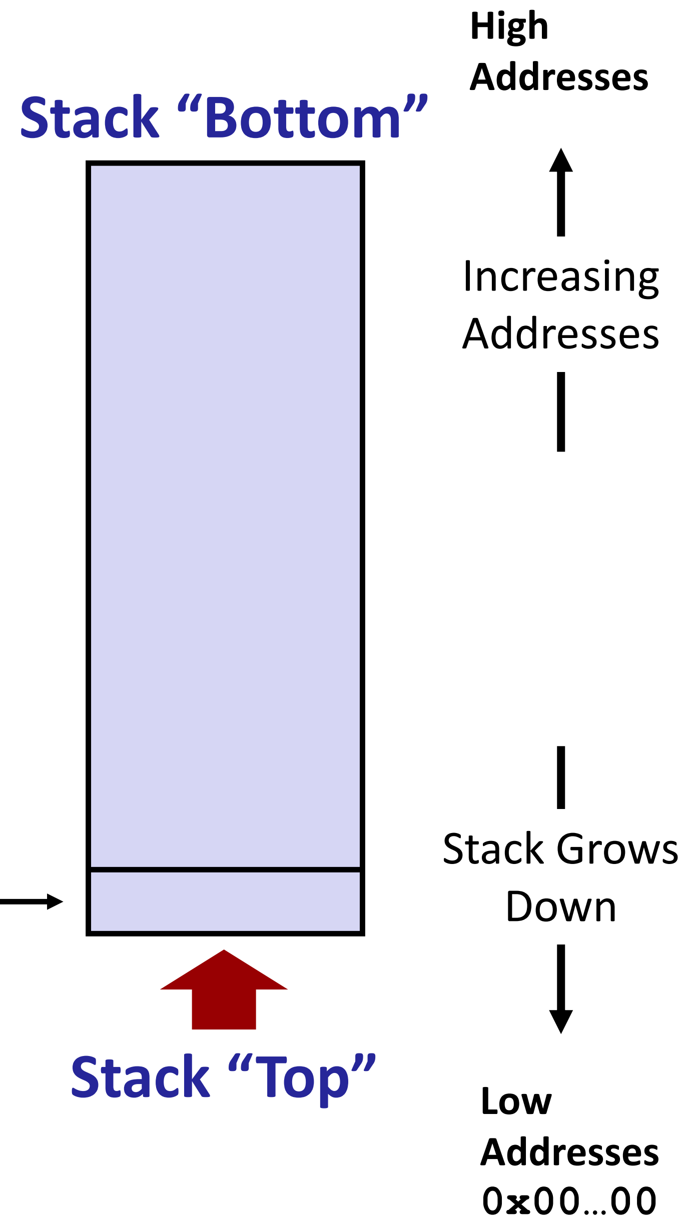

- Segmentation fault: impermissible memory access

# x86-64 Stack (Review)

- Region of memory managed with stack “discipline”
  - Grows toward lower addresses
  - Customarily shown “upside-down”

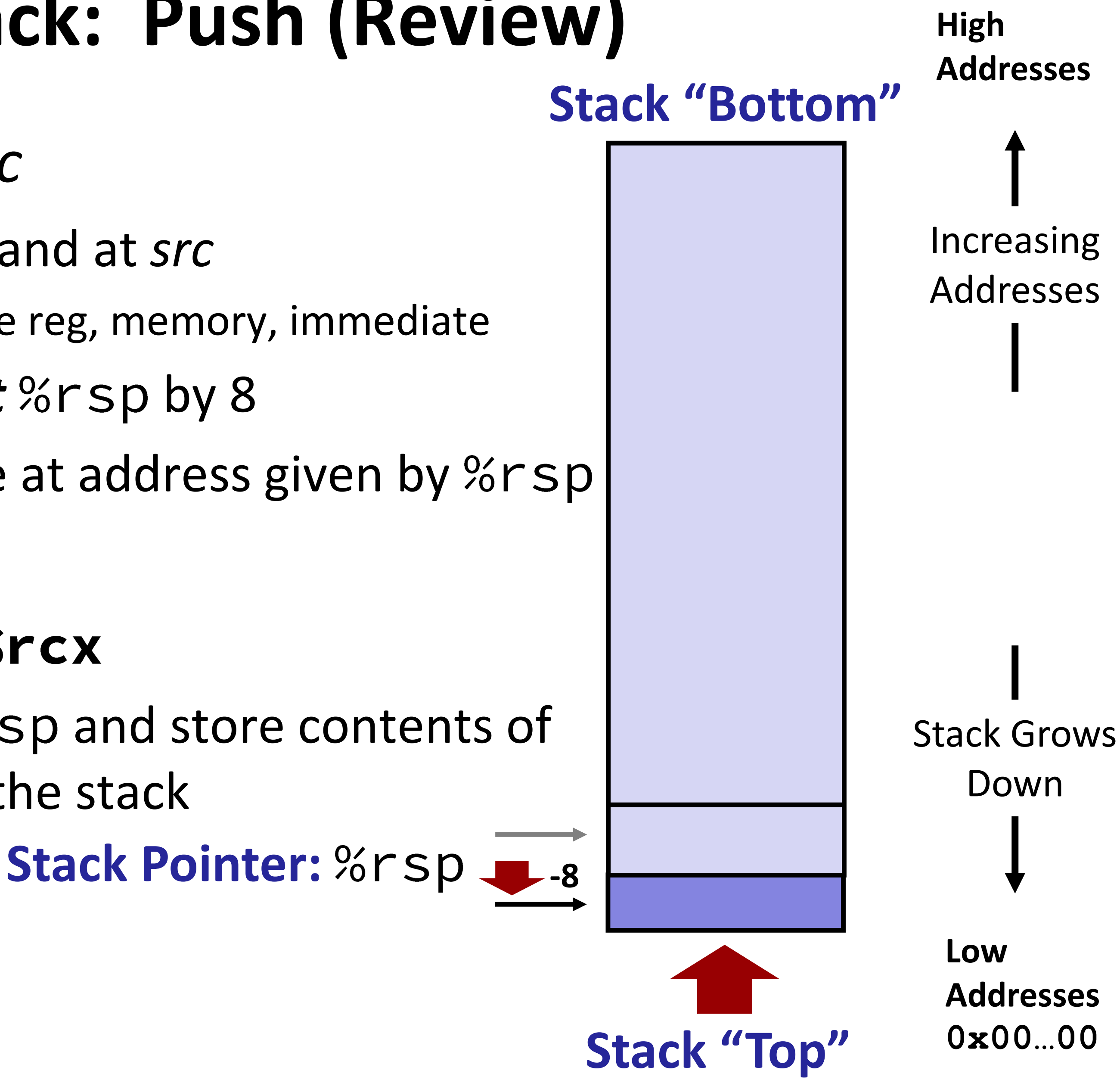
- Register `%rsp` contains *lowest* stack address
  - `%rsp` = address of *top* element, the most-recently-pushed item that is not-yet-popped

**Stack Pointer:** `%rsp`



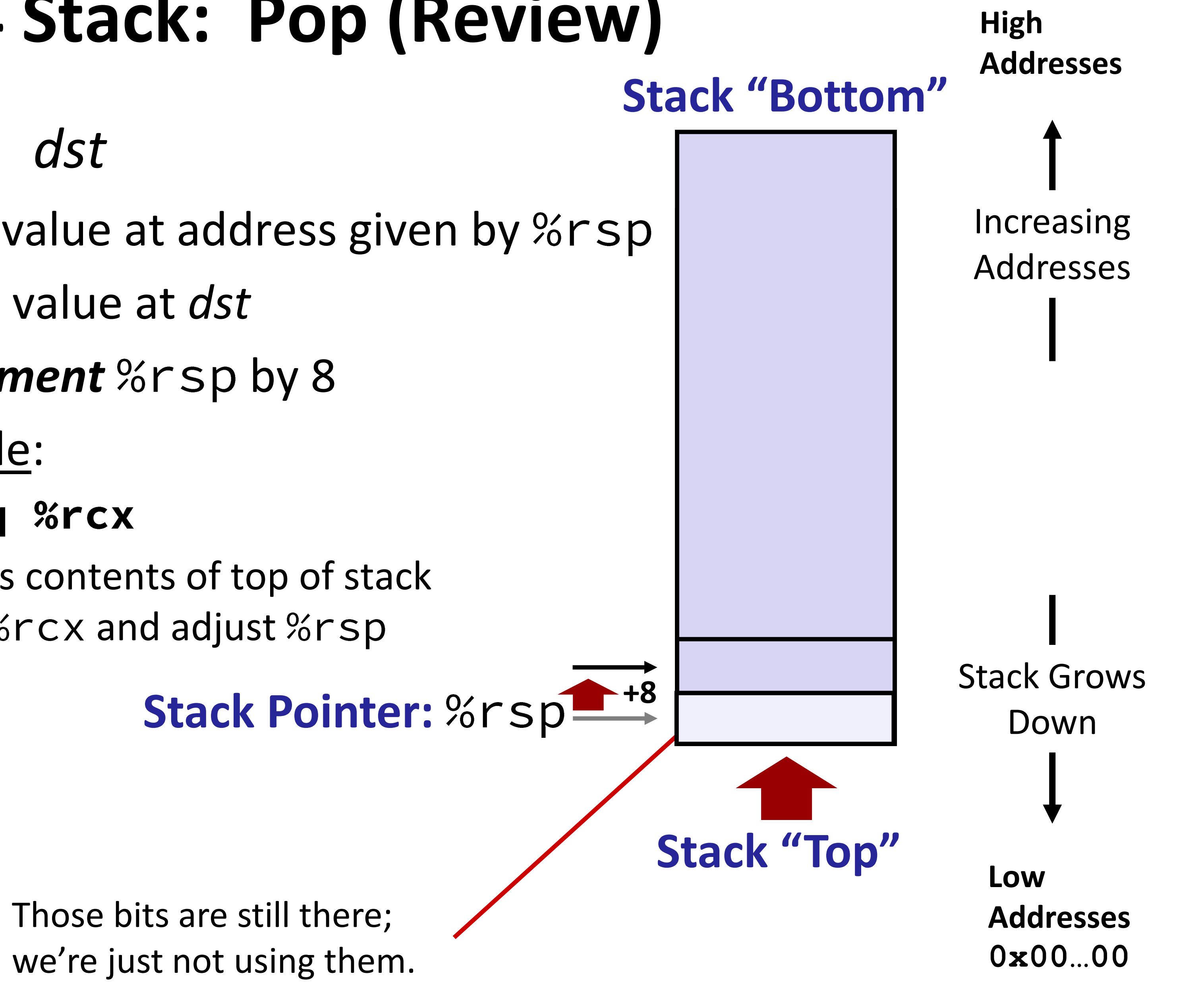
# x86-64 Stack: Push (Review)

- `pushq` *src*
  - Fetch operand at *src*
    - *Src* can be reg, memory, immediate
  - ***Decrement*** `%rsp` by 8
  - Store value at address given by `%rsp`
- Example:
  - **`pushq %rcx`**
  - Adjust `%rsp` and store contents of `%rcx` on the stack



# x86-64 Stack: Pop (Review)

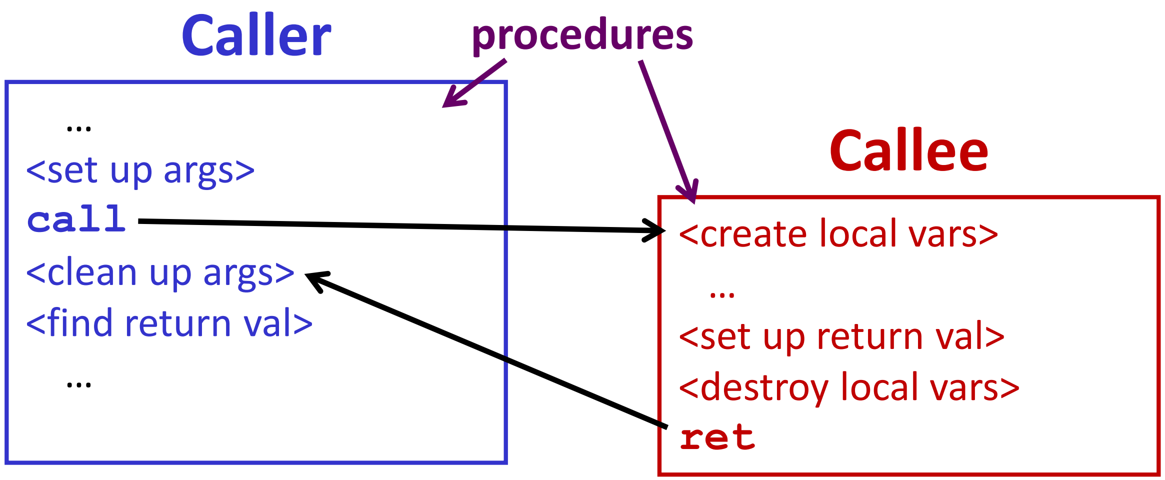
- popq *dst*
  - Load value at address given by `%rsp`
  - Store value at *dst*
  - ***Increment*** `%rsp` by 8
- Example:
  - **`popq %rcx`**
  - Stores contents of top of stack into `%rcx` and adjust `%rsp`



# Procedures

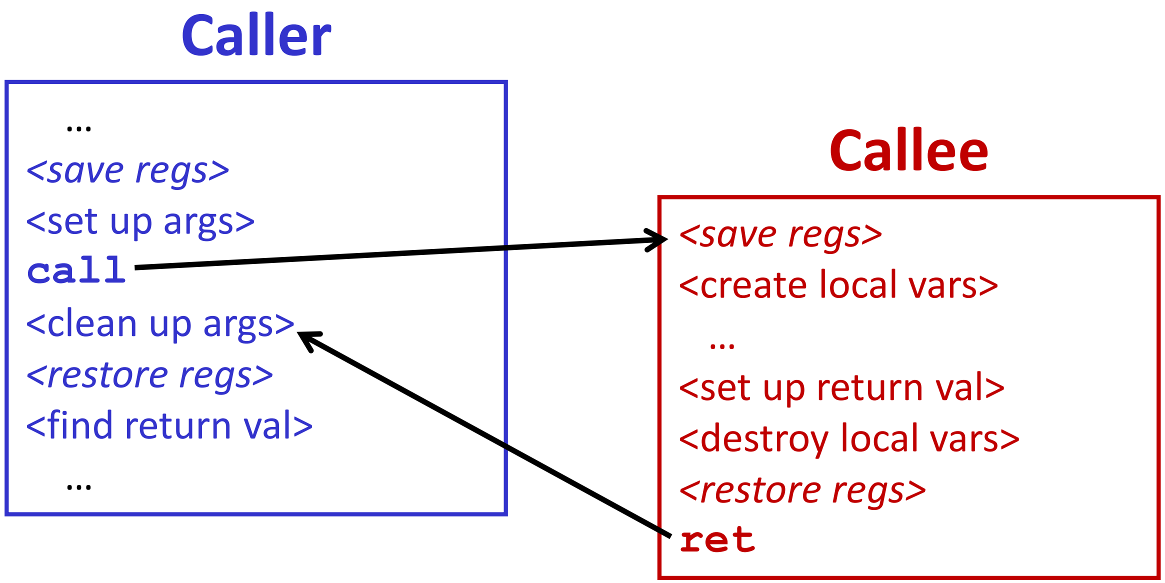
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

# Procedure Call Overview




- **Callee** must know where to find args
- **Callee** must know where to find *return __address__*
- **Caller** must know where to find *return __value__*
- **Caller** and **Callee** run on same CPU, so use the same registers
  - How do we deal with register reuse?
- Unneeded steps can be skipped (*e.g.*, no arguments)

# Procedure Call Overview




- The *convention* of where to leave/find things is called the calling convention (or procedure call linkage)
  - Details vary between systems
  - We will see the convention for <u>x86-64/Linux</u> in detail
  - What could happen if our program didn't follow these conventions?

# Code Example (Preview)

```
void multstore
 (long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  400540: push   %rbx            # Save %rbx
  400541: movq   %rdx,%rbx       # Save dest
  400544: call   400550 <mult2>  # mult2(x,y)
  400549: movq   %rax,(%rbx)     # Save at dest
  40054c: pop    %rbx            # Restore %rbx
  40054d: ret                    # Return
```

Compiler Explorer:
https://godbolt.org/z/Yb3GeoaMa

```
long mult2
  (long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax  # a
  400553:  imulq  %rsi,%rax  # a * b
  400557:  ret               # Return
```

# Procedure Control Flow (Review)

- Use stack to support procedure call and return
- Procedure call: `call label`
  1) Push return address on stack (*why? which address?*)
  2) Jump to ***`label`***

# Procedure Control Flow (Review)

- Use stack to support procedure call and return
- Procedure call: `call label`
  1) Push return address on stack (*why? which address?*)
  2) Jump to ***label***
- Return address:
  - Address of instruction immediately after **`call`** instruction
  - Example from disassembly:

```
400544: call    400550 <mult2>
400549: movq    %rax,(%rbx)
```

Return address = **0x400549**

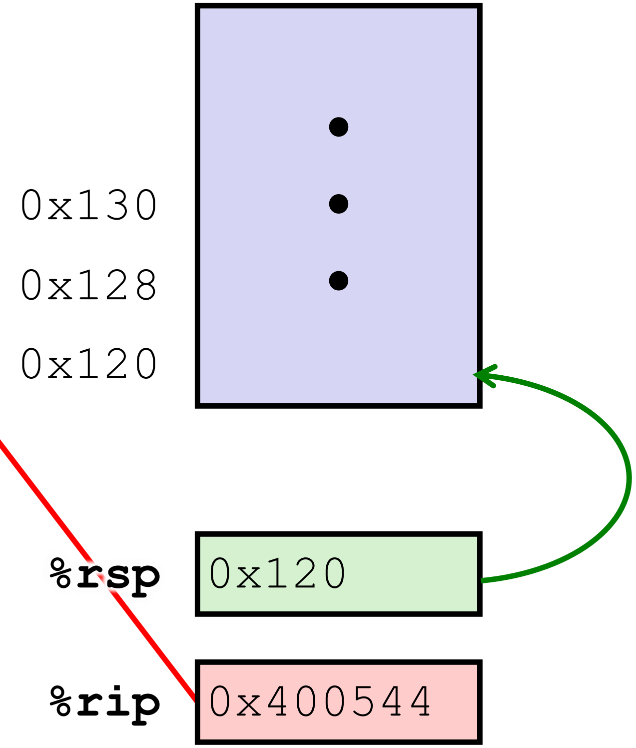
next instruction happens to be a move, but could be anything

- Procedure return: `ret`
  1) Pop return address from stack
  2) Jump to address

# Procedure Call Example (step 1)

```
0000000000400540 <multstore>:
  •
  •
  400544: call    400550 <mult2>
  400549: movq    %rax,(%rbx)
  •
  •
```

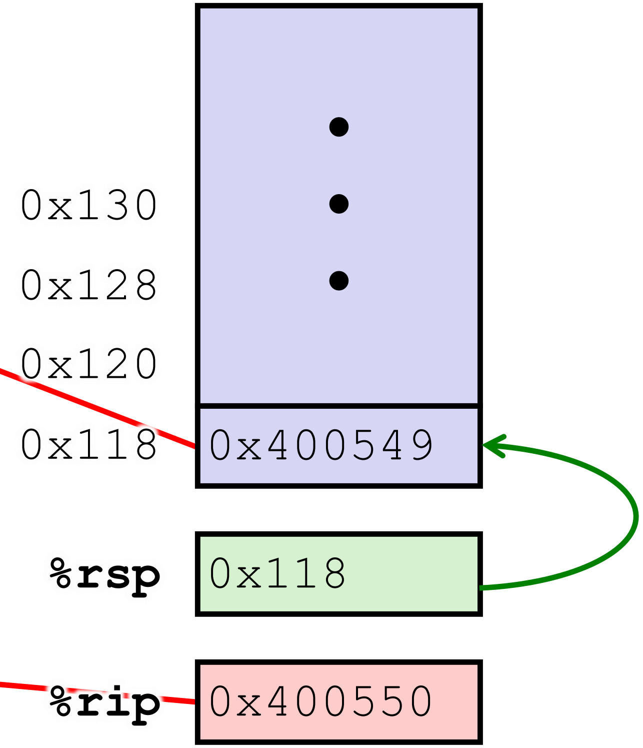
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



# Procedure <u>Call</u> Example (step 2)

```
0000000000400540 <multstore>:
  •
  •
  400544: call   400550 <mult2>
  400549: movq   %rax,(%rbx)
  •
  •
```

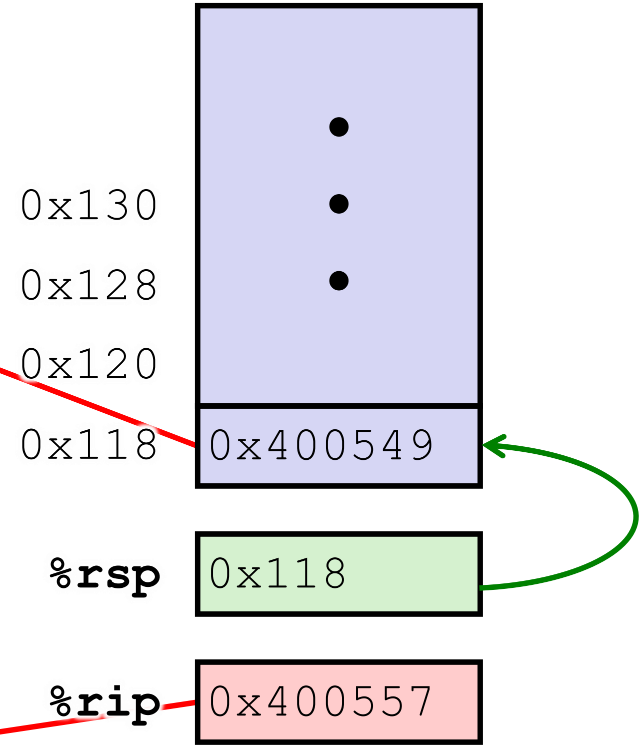
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



# Procedure Return Example (step 1)

```
0000000000400540 <multstore>:
  •
  •
  400544: call    400550 <mult2>
  400549: movq    %rax,(%rbx)
  •
  •
```

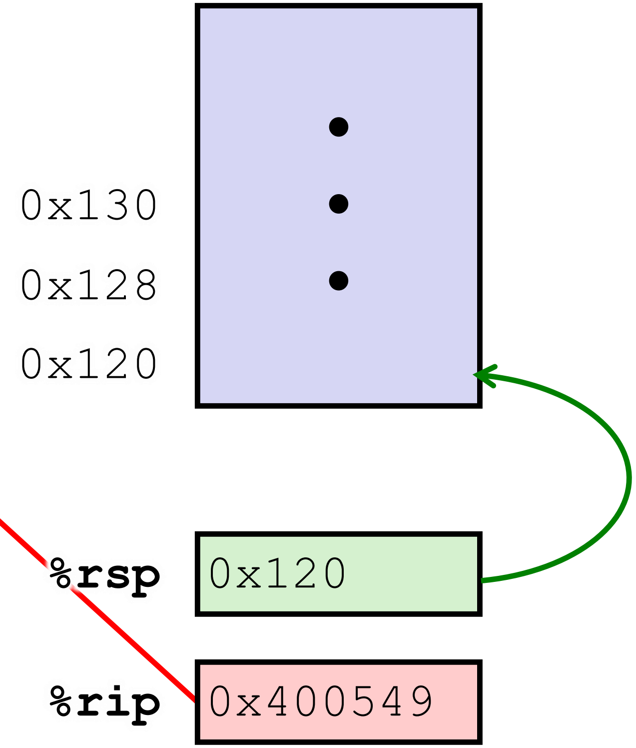
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



# Procedure Return Example (step 2)

```
0000000000400540 <multstore>:
  •
  •
  400544: call    400550 <mult2>
  400549: movq    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  movq    %rdi,%rax
  •
  •
  400557:  ret
```



# Procedures

- Stack Structure
- **Calling Conventions**
  - Passing control
  - **Passing data**
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

# Procedure Data Flow (Review)

## Registers (NOT in Memory)

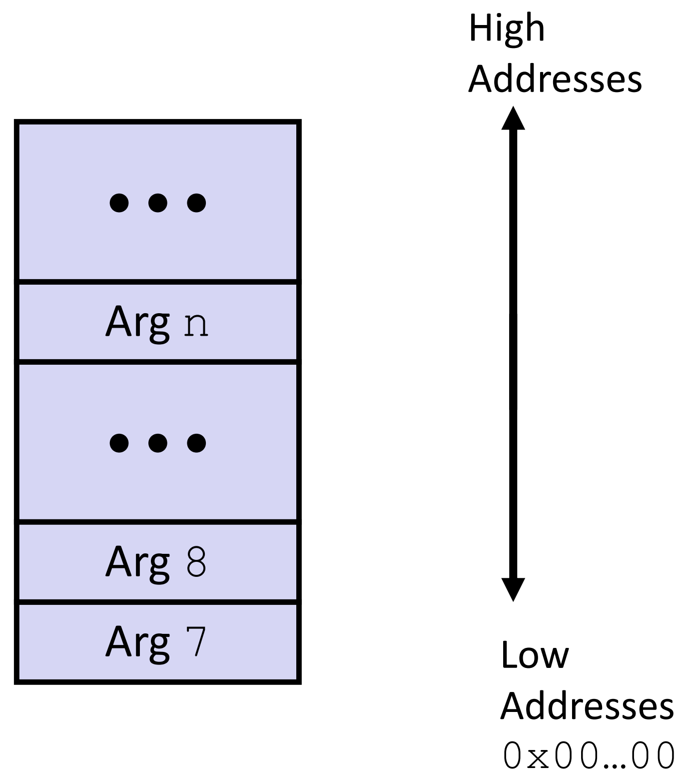
- First 6 arguments

| | |
|---|---|
| `%rdi` | *Diane's* |
| `%rsi` | *Silk* |
| `%rdx` | *Dress* |
| `%rcx` | *Costs* |
| `%r8` | *$8 9* |
| `%r9` | |

- Return value

`%rax`

## Stack (Memory)




- Only allocate stack space when needed

# x86-64 Return Values

- By convention, values returned by procedures are placed in `%rax`
  - Choice of `%rax` is arbitrary

1) Caller must make sure to save the contents of `%rax` before calling a callee that returns a value
   - Part of register-saving convention

2) Callee places return value into `%rax`
   - Any type that can fit in 8 bytes – integer, float, pointer, etc.
   - For return values greater than 8 bytes, best to return a *pointer* to them

3) Upon return, caller finds the return value in `%rax`

# Data Flow Examples

```
void multstore
 (long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, dest in %rdx
    • • •
  400541: movq   %rdx,%rbx        # Save dest
  400544: call   400550 <mult2> # mult2(x,y)
  # t in %rax
  400549: movq   %rax,(%rbx)      # Save at dest
    • • •
```

```
long mult2
  (long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  movq   %rdi,%rax  # a
  400553:  imulq  %rsi,%rax  # a * b
  # s in %rax
  400557:  ret               # Return
```

# Procedures

- Stack Structure
- **Calling Conventions**
  - Passing control
  - Passing data
  - **Managing local data**
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# Stack-Based Languages

- Languages that support recursion
  - *e.g.*, C, Java, most modern languages
  - Code must be *re-entrant*
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store *state* of each instantiation
    - Arguments, local variables, return address
- Stack allocated in *frames*
  - State for a single procedure instantiation
- Stack discipline
  - State for a given procedure needed for a limited time
    - Starting from when it is called to when it returns
  - Callee always returns before caller does

# Call Chain Example

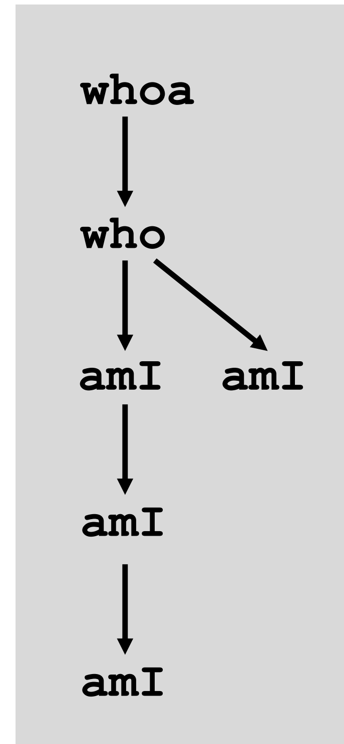
```
whoa(…)
{
    •
    •
    who();
    •
    •
}
```

```
who(…)
{
    •
    amI();
    •
    amI();
    •
}
```

```
amI(…)
{
    •
    if(…){
      amI()
    }
    •
}
```

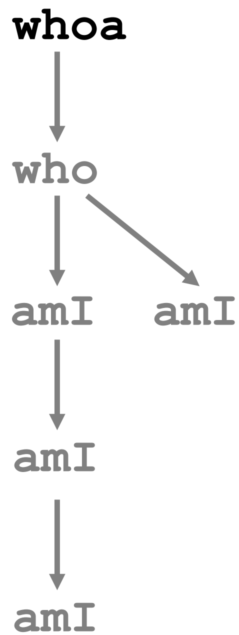
Procedure `amI` is recursive (calls itself)

Example Call Chain

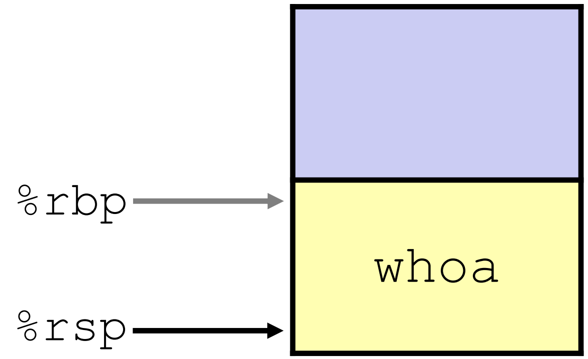


# 1) Call to whoa

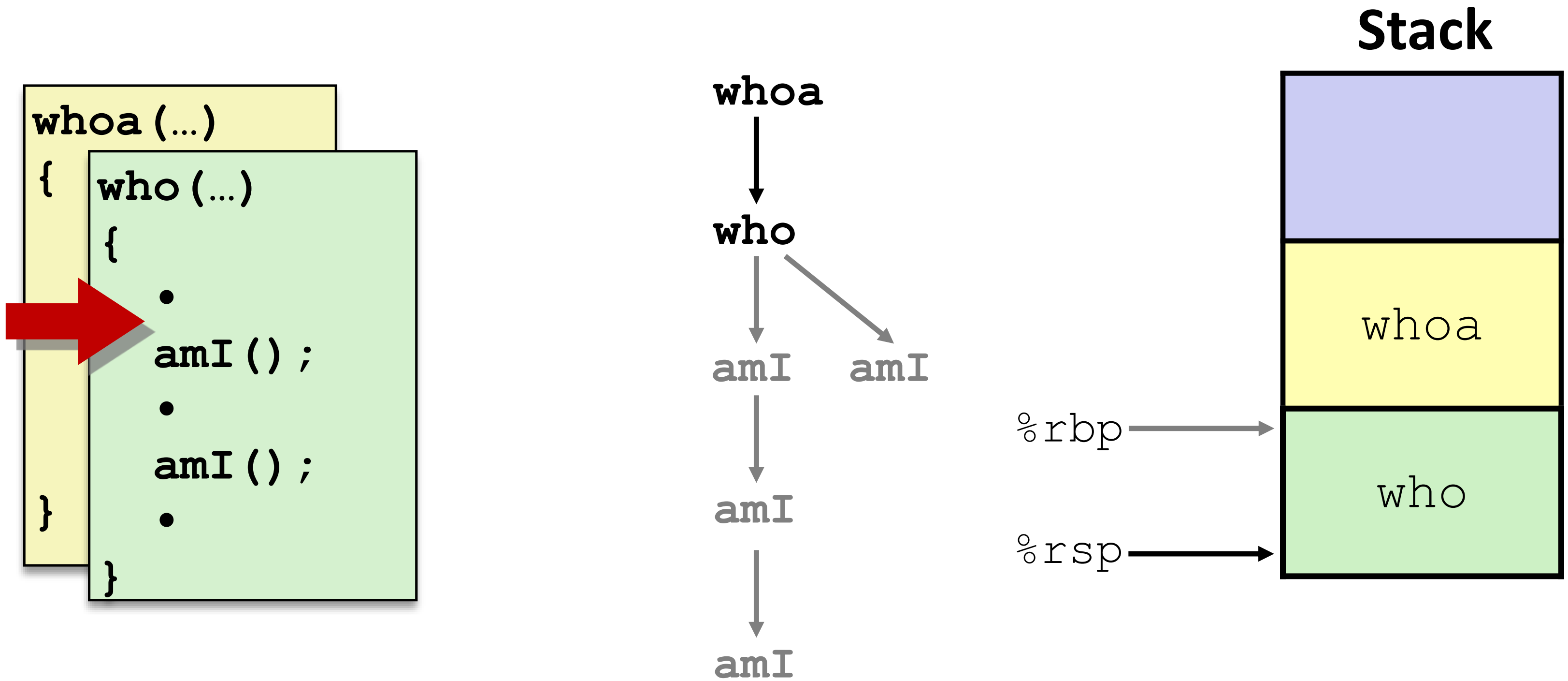
```
whoa(…)
{
  •
  •
  who();
  •
  •
}
```



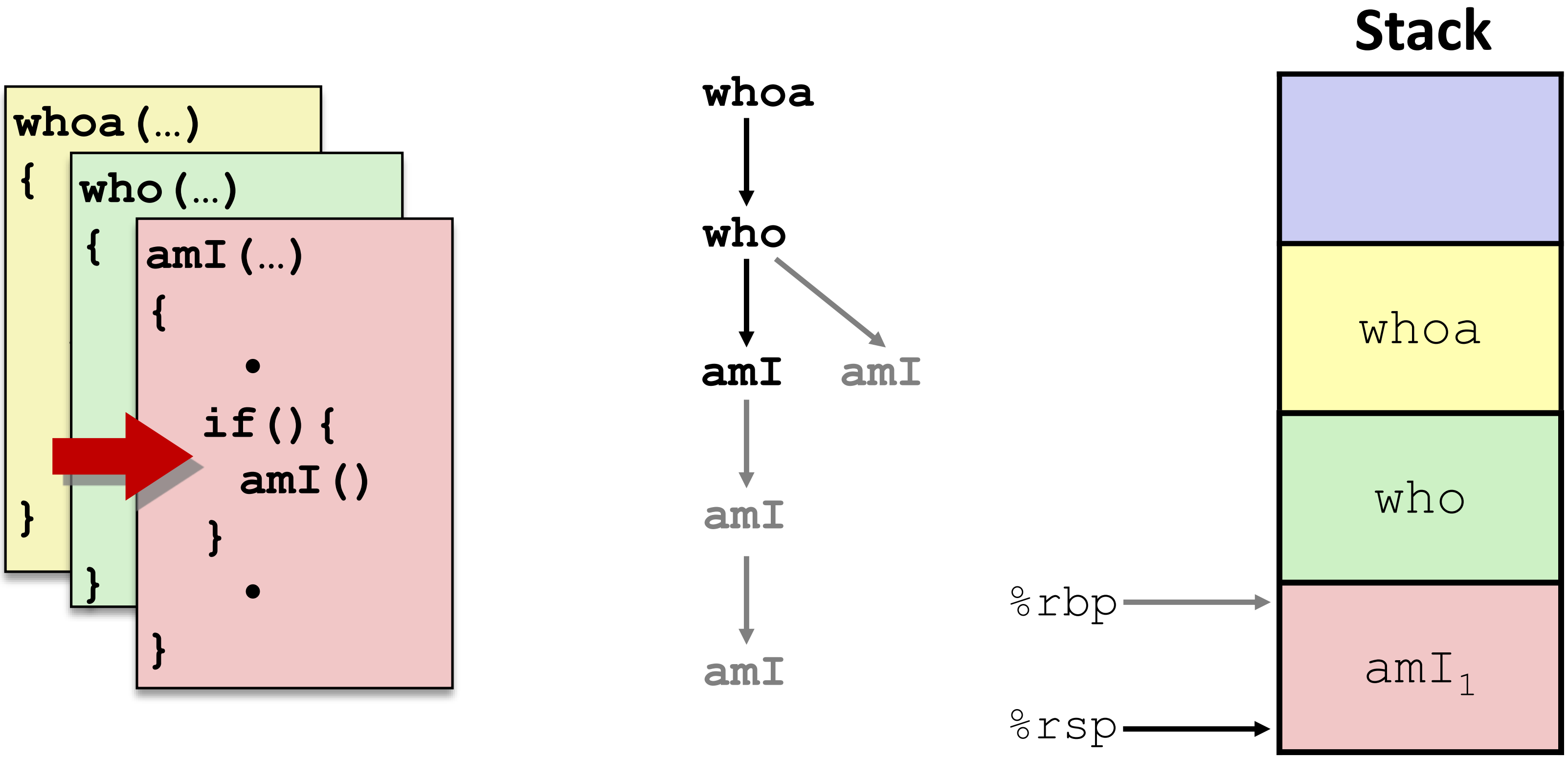

Stack



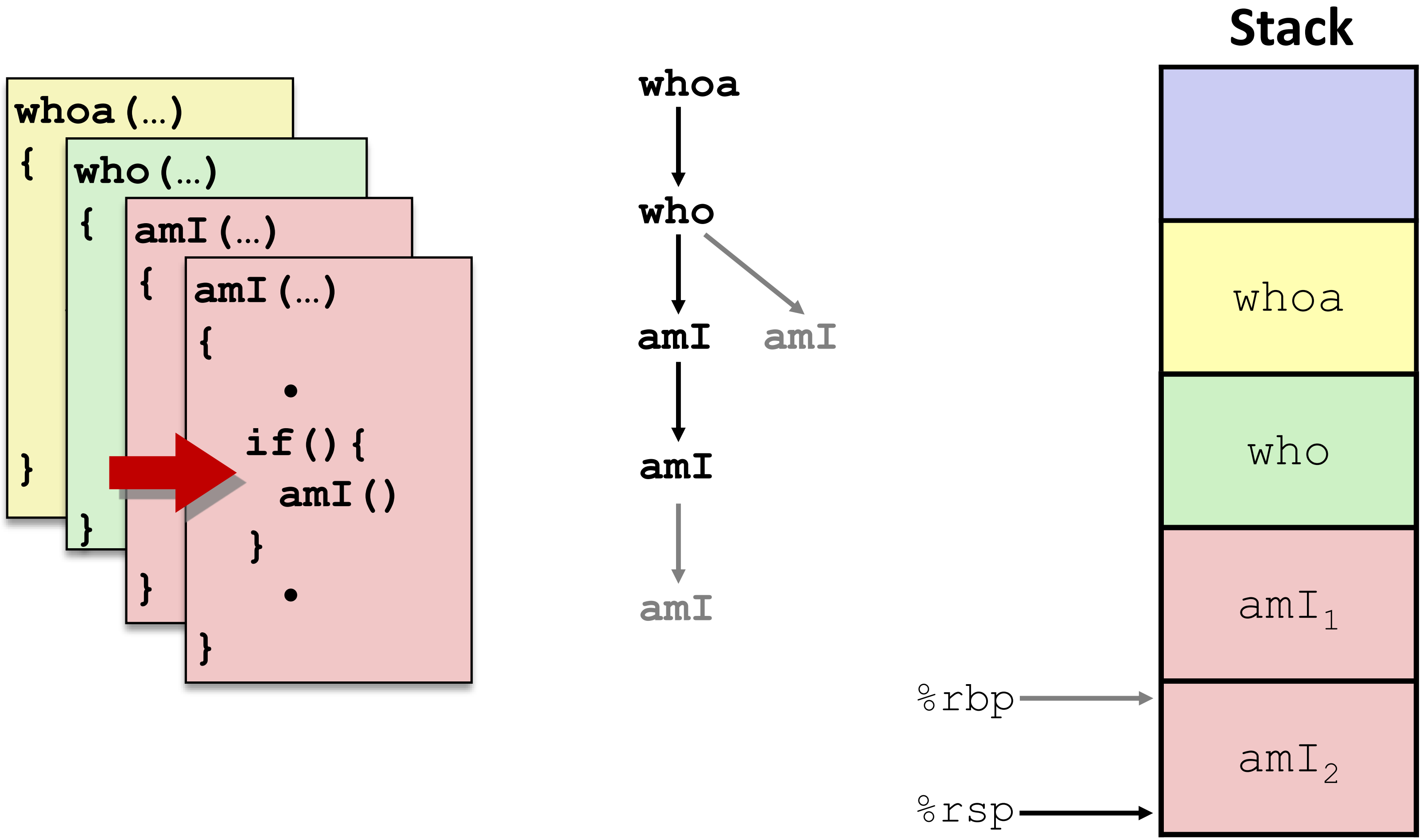
# 2) Call to who


whoa(…)
{
}
who(…)
{
•
amI();
•
amI();
•
}
whoa
who
amI
amI
amI
amI
Stack
whoa
who
%rbp
%rsp

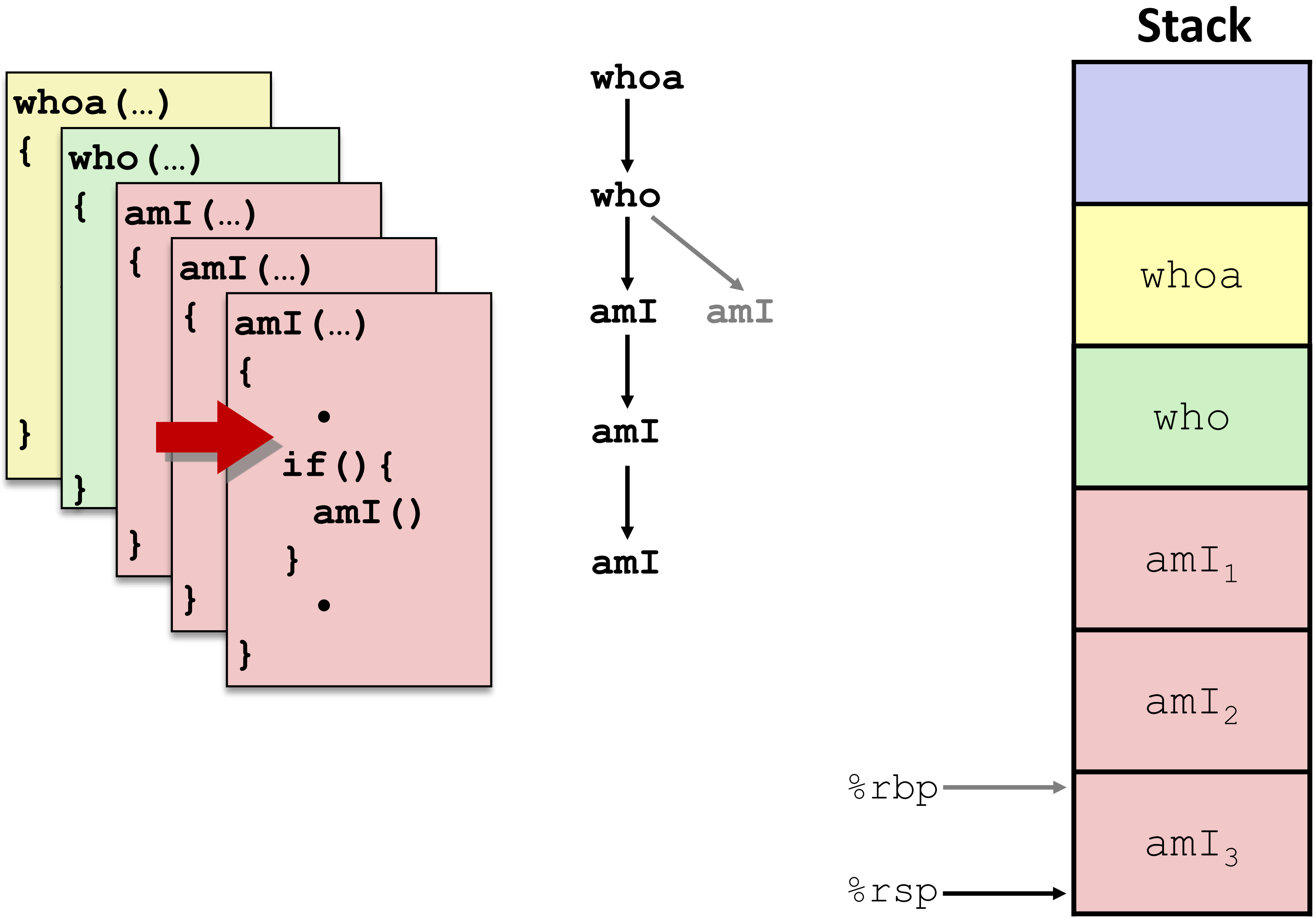
# 3) Call to amI (1)



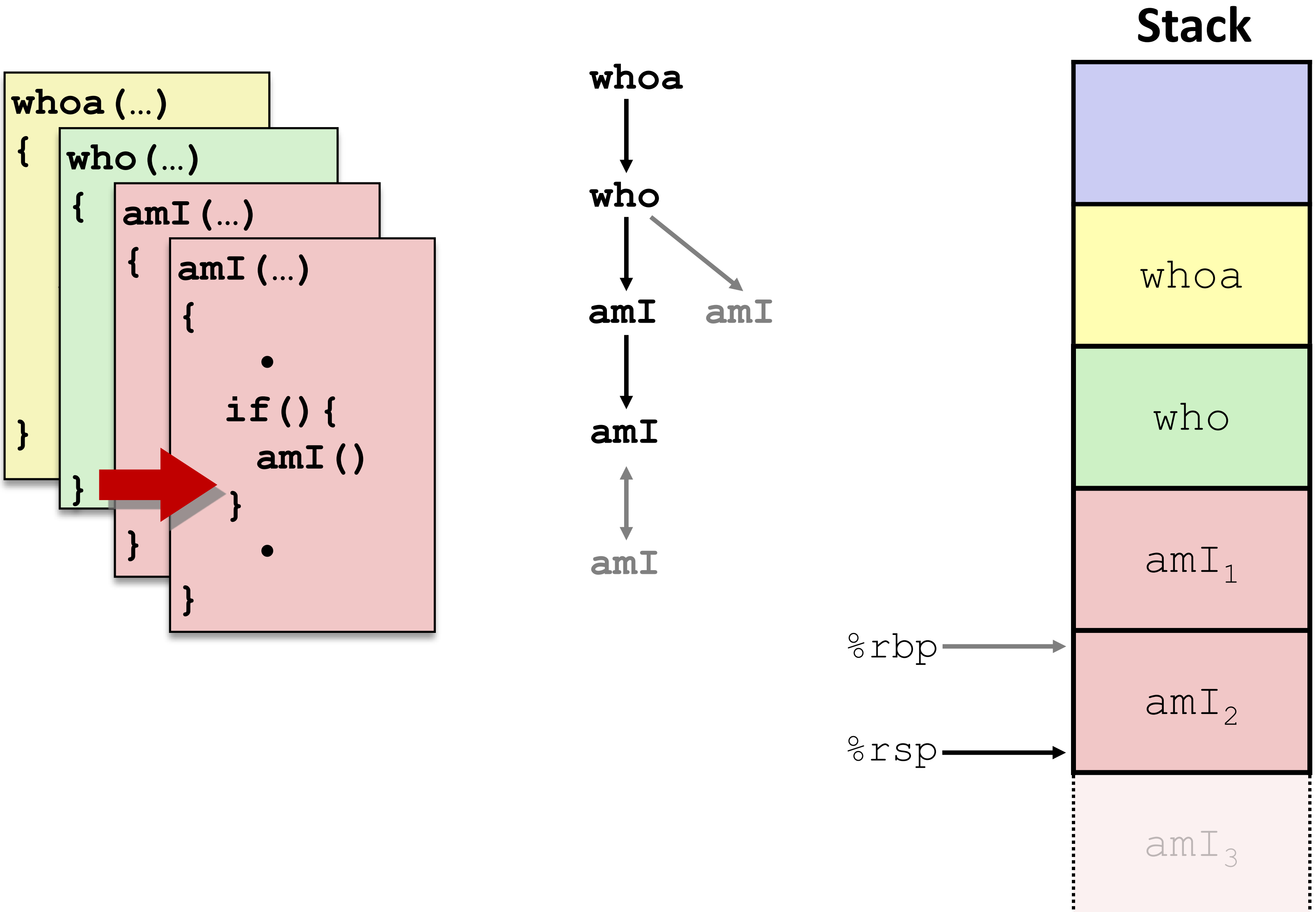
# 4) Recursive call to amI (2)



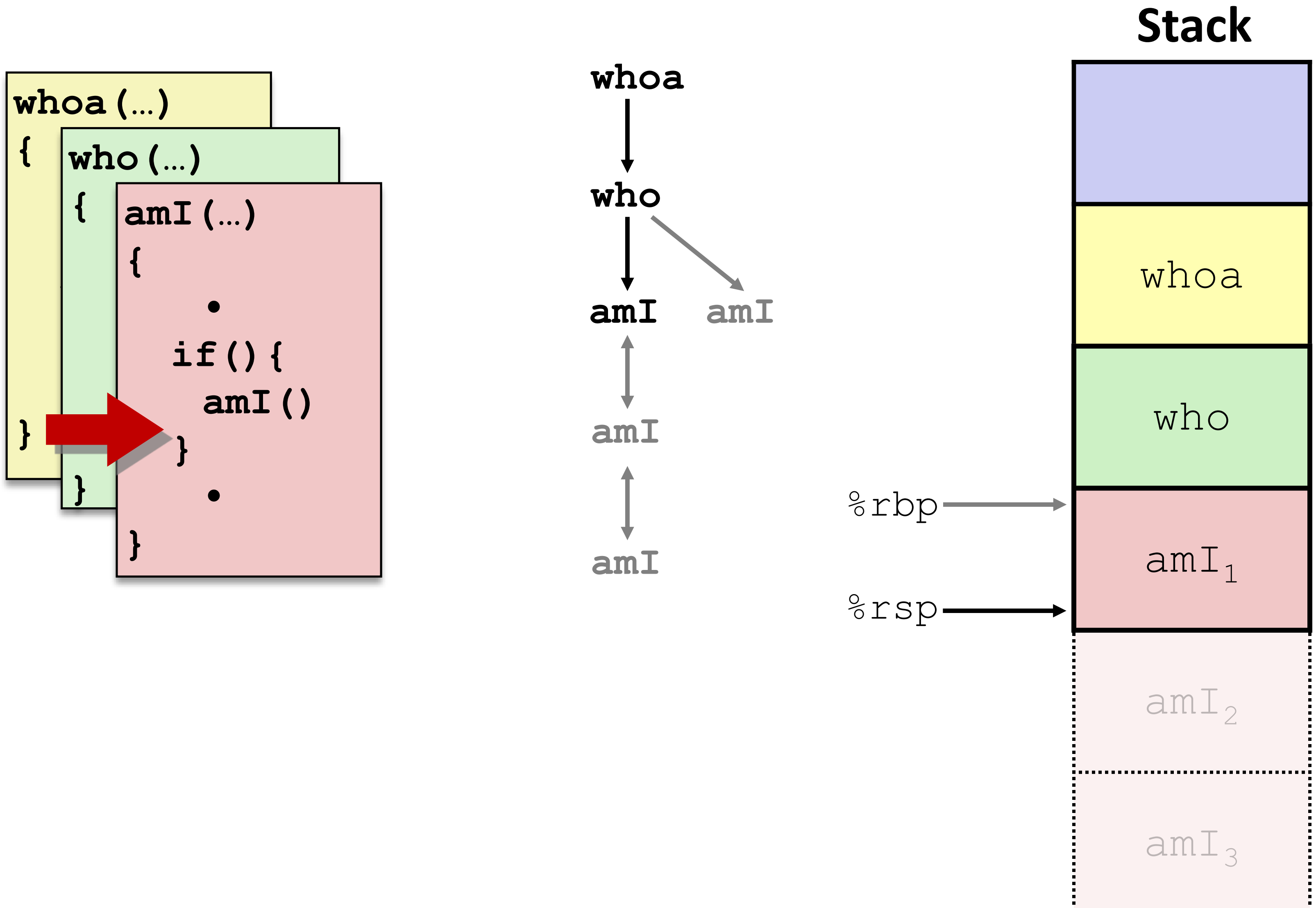
# 5) (another) Recursive call to amI (3)



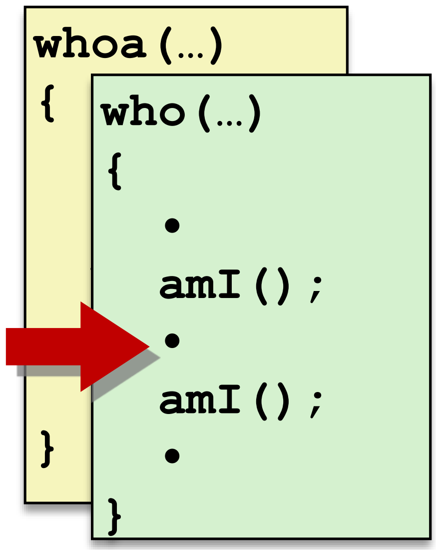
# 6) Return from (another) recursive call to `amI`

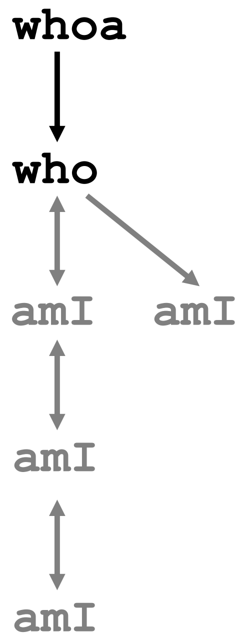


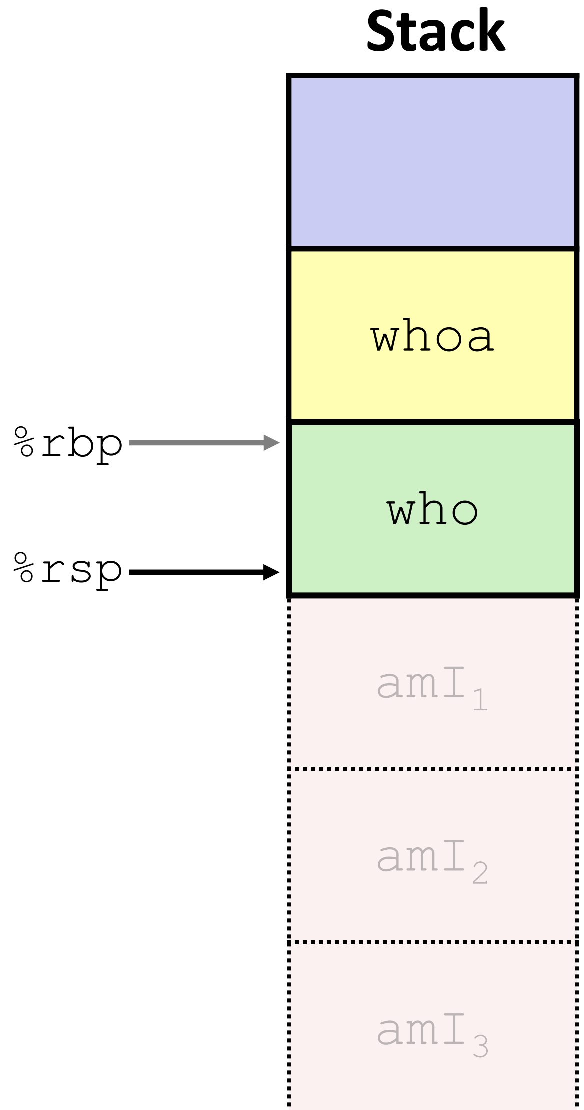
# 7) Return from recursive call to amI



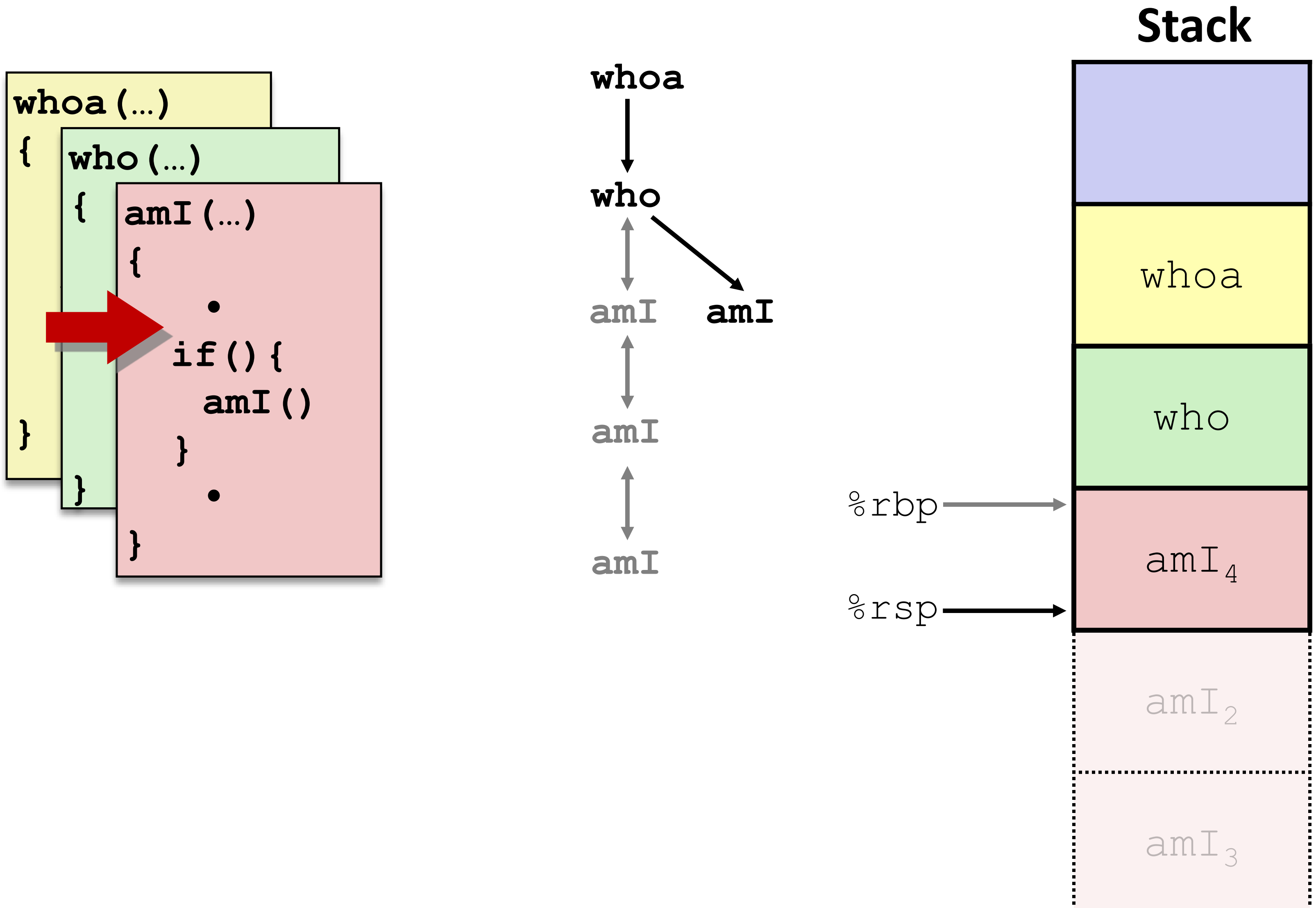
# 8) Return from call to amI



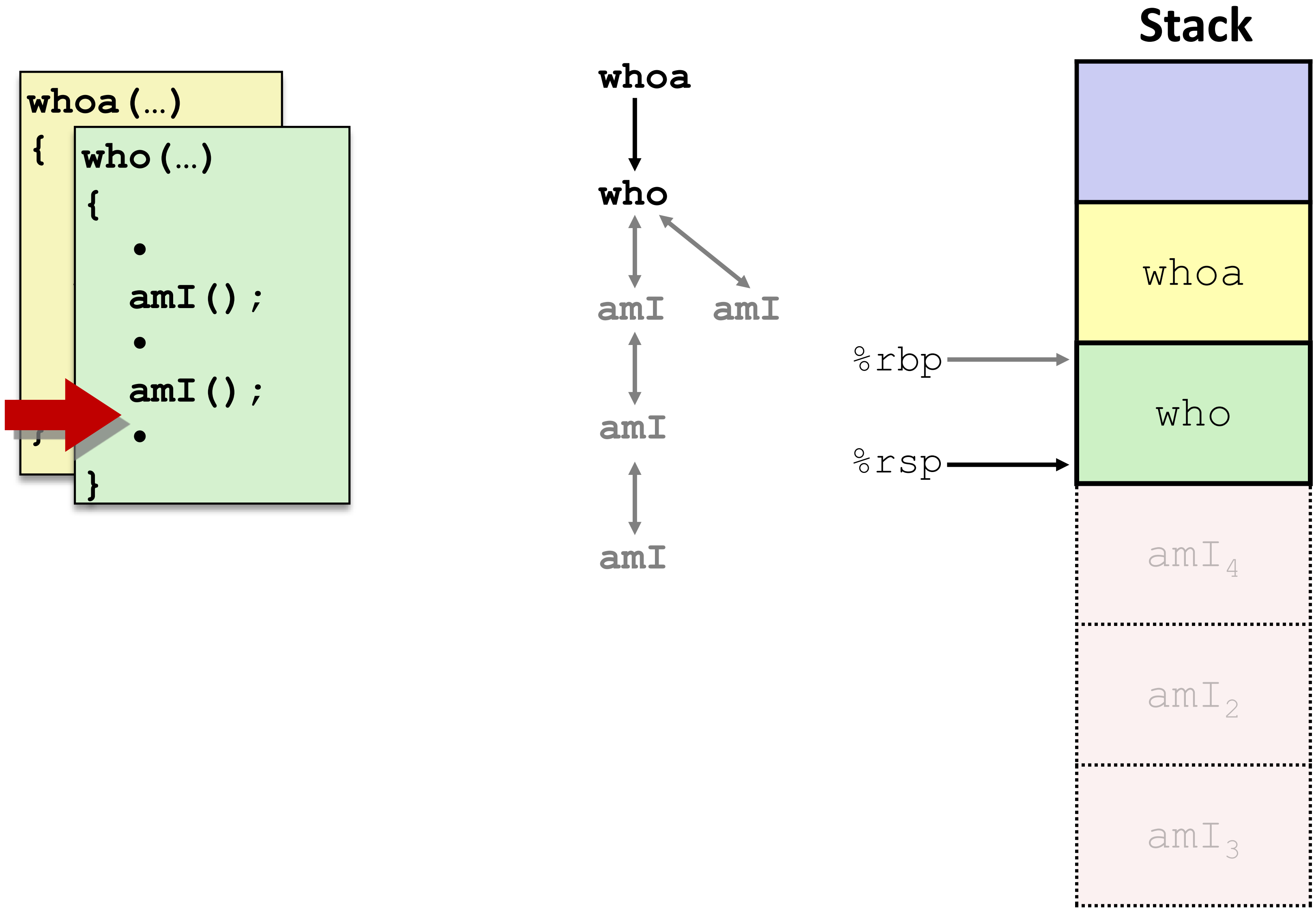



# 9) (second) Call to amI (4)



# 10) Return from (second) call to `amI`



# 11) Return from call to who

```
whoa(…)
{
   •
   •
   who();
   •
   •
}
```